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Traditional leakage models for leakage modelling: effective or not?

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Abstract

Accurate models are critical for the effective management of leaks in our water distribution systems. The increased use of plastic pipes has emphasised the need to assess the ability of current leakage assessment tools in quantifying the real losses from complex time and pressure dependent leaks. The numerical study presented in this paper shows that traditional Minimum Night Flow (MNF) analyses provide good approximations of the leak response, when the loading history and discrete pressure regimes are accounted for, of leaks in viscoelastic pipe. The time and dependent nature of such leaks are of greater significance when the response to short time period pressure transients are quantified, important for active leakage control methodologies in particular.

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Keywords: Leakage management; modelling; viscoelasticity

1. Introduction and Background

Minimising the total real losses (background leakage and bursts) from water distribution systems is essential in improving the overall sustainability of our potable water supply. Leakage assessment is crucial in understanding the performance of current infrastructure and determining effective ways to manage and reduce quantified levels of leakage. Traditional leakage models are founded on Torricelli's theorem, assuming that leaks behave as orifices. The Generalised Orifice Equation, Equation 1, provides an effective tool to capture the leakage behaviour of both individual leaks [1] but also the characteristic leakage response of an isolated system (e.g. District Metered Area (DMA)[2]).

$$Q = ACd\sqrt{2gH} = cH^{\lambda} \tag{1}$$

c is the leakage coefficient and λ is the leakage exponent. It is generally accepted that leaks are more sensitive to pressure than described by the traditional fixed area Orifice Equation, highlighted by empirically derived leakage exponent values greater than 0.5 from both laboratory tests and field investigations [2]. This is predominantly due to the dynamic nature of the leak area [1,3]. Various studies have focussed on the development of leakage models accounting for the observed pressure-dependent leakage. Research has included numerical and physical studies aimed at quantifying the structural deformations of leaks in order to determine an associated leakage exponent, as well as

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field work aimed at characterising the total system leakage behaviour. The majority of these studies assume a one-to-one relationship between the system pressure and the resulting leakage flow-rate. However, this is only valid for linear-elastic materials where the pressure dependent leak areas display a Hookean type structural response. Leaks in commonly used plastic pipes, such as polyethylene, have been shown to result in a more complex relationship between pressure and leakage flow-rate due to the inherent material properties; namely viscoelasticity [4]. [5] showed that linear-elastic leak area models [6] produced 'good approximations' of the leakage response of cracks in viscoelastic pipes over a two day period when fitting to experimental data, but the cumulative error increases with increasing time. The time (loading history and leak age) and pressure dependence of these leaks means that the synchronous leakage flow-rate may only be described by the Orifice Equation with the inclusion of the time and pressure dependent leak area, as shown in Equation 2. Generalising this reformulation of the Orifice Equation is therefore not a trivial matter.

$$Q(t, H) = A(t, H)Cd\sqrt{(2gH)} \tag{2}$$

Leakage management may be categorised as 1) Leakage Assessment 2) Leakage Detection and 3) Leakage Control [7]. Each of these categories depend on the accurate definition of leakage models. Leakage assessment is typically carried out using 'bottom-up' approaches such as MNF analyses which fit a theoretical leakage exponent to the observed MNF measurements in an isolated DMA; once again assuming a one-to-one relationship between pressure and leakage. Leakage detection and localisation methodologies such as inverse transient analysis utilise the Orifice Equation to numerically account for the damping effect of a leak on a generated pressure signal, in order to evaluate the existence and location of a failure within a length of pipe [8]. Finally, pressure management strategies for leakage control depend on the definition of a characteristic theoretical leakage exponent to determine the benefit of pressure reduction using the Fixed and Variable Area Discharge (FAVAD) framework [9]. All of these management schemes have been demonstrated to be effective means of improving the sustainability of water distribution systems. However with the increasing use of plastic pipes by the water industry due to the inherent flexibility, durability and ease of use, the effectiveness of these current approaches to account for the highlighted complex leakage behaviour of leaks in viscoelastic materials is a relatively unexplored topic.

2. Investigation Aims

The need for different levels of modelling accuracy, for activities from planning pressure reduction schemes to the application of modelling transients for the detection and localisation of leaks, necessitates a need to explore the general applicability of current leakage models. The aim of this study is to evaluate the capability of current leakage modelling practice in capturing the leakage behaviour of individual leaks for both linear-elastic but primarily viscoelastic pipe materials, highlighting the potential strengths and weaknesses.

3. Methodology

In order to assess the effectiveness of traditional leakage assessment methodologies in capturing the complex pressure-leakage relationship of leaks in viscoelastic pipes, an arbitrary longitudinal crack (60x1 mm) in representative polyethylene (PE) pipe (SDR11, ⊘ 63 mm) was simulated. A validated viscoelastic leak area model was utilised, accounting for the magnitude of the leak area change, dependent on the geometry of the leak and pipe, boundary conditions (pressure loading) and the material properties. The leakage flow-rate was modelled using the modified Orifice Equation given in Equation 2, including a constant discharge coefficient, the use of which has been verified in supplementary physical investigations.

3.1. Minimum Night Flow Analysis

Leak assessment may be segregated into two categories; top-down and bottom-up approaches [7]. MNF analysis is a common bottom-up approach that uses DMA flow and pressure data from a window of minimum legitimate usage to evaluate the theoretical leakage coefficient and leakage exponent. These system descriptors are then used to estimate the total leakage (real losses) from the isolated DMA using the average system time series pressure for a specified duration (e.g. pressure measurements for 24 hour period at 15 minute intervals).

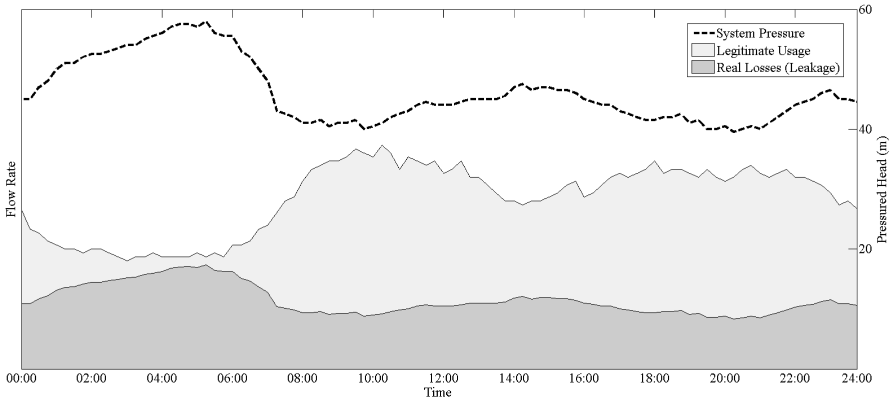

Fig. 1. Sample DMA flow-rate and pressure head time series, highlighting MNF (maximum leakage) approximately between 02:00 and 06:00.

Figure 1 is a simulated example of data used for such MNF calculations. The minimum flow is between approximately 02:00 and 06:00 (typically between 02:00 and 04:00 [10]) where the legitimate usage is at a minimum. The pressure and flow data for this time period alongside the generalised orifice equation, Equation 1, is used to fit the system descriptors described and extrapolated to estimate the leakage response over a larger time frame.

Adopting the MNF analysis framework and the arbitrary leak model described (test case 1), the accuracy of the leakage exponent approach for estimating leakage for viscoelastic pipes was evaluated. Three different test cases (2-4) were also assessed, as listed in Table 1, based on standard PE pipe sections [11], alongside the influence of loading history (age of leak) and different pressure regimes. A representative diurnal pressure cycle was simulated for the analysis.

Table 1. Pipe and longitudinal crack dimensions for modelling study.

Test Case	Pipe Diameter (mm)	Wall Thickness (mm)	Crack Length (mm)	Crack Width (mm)
1	63	6.5	60	1
2	50	5.2	40	2
3	90	9.2	80	1
4	200	20.2	120	1

Finally, an assessment of the significance of the viscoelastic behaviour of leaks in plastic pipes was conducted for the response to rapid pressure changes (pressure transients). The response of equivalent (equal initial area prior to application of transient pressure wave) single fixed area orifices, linear elastic and viscoelastic leaks were compared.

4. Results and Analysis

An example of the MNF analysis and fitting procedure is presented in Figure 2 showing the input pressure head data, simulated leakage flow rate, extrapolated MNF data points (soild grey circles) and the subsequent exponent fitting and comparison of the simulated (*'Visco Model'*) and *'Fitted Model'* net leakage flow. The pressure data was sampled at 15 minute intervals, representative of a common sampling frequency used by the water industry. Figure 2 is the result from analysis of Test Case 1 with a total pressurisation period of 48 hours. In context, this hypothetical scenario is equivalent to the formation of a leak at t=0 days, and the completion of the MNF analysis at t=1 days (leak age).

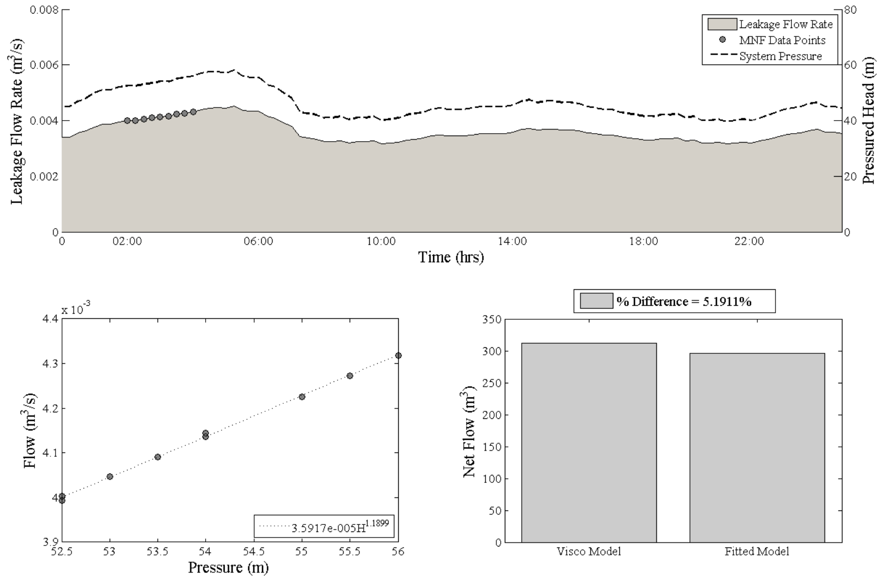

Fig. 2. Example of MNF analysis using FAVAD model to determine leakage exponent and compare viscoelastic leakage model with fitted data. Pressure and flow data sampled at 15 minute intervals.

It can be seen in Figure 2 that the fitted model under-predicted the simulated flow volume by 5.19% over a 24 hour period. The fitted leakage exponent of 1.19 highlights the sensitivity of this leak type to changes in pressure, greater than is described by the traditional Orifice Equation when assuming a fixed leak area. To understand the effect of the leak age (loading history) on the leak sensitivity and also the accuracy of the Generalised Orifice Equation in capturing the viscoelastic leakage behaviour, a range of leak ages were investigated using Test Cases 2-4. Figure 3 shows the associated leakage exponents derived from the MNF analysis and the percentage difference of the simulated leak and fitted model for leaks subject to a repeated diurnal pressure trace.

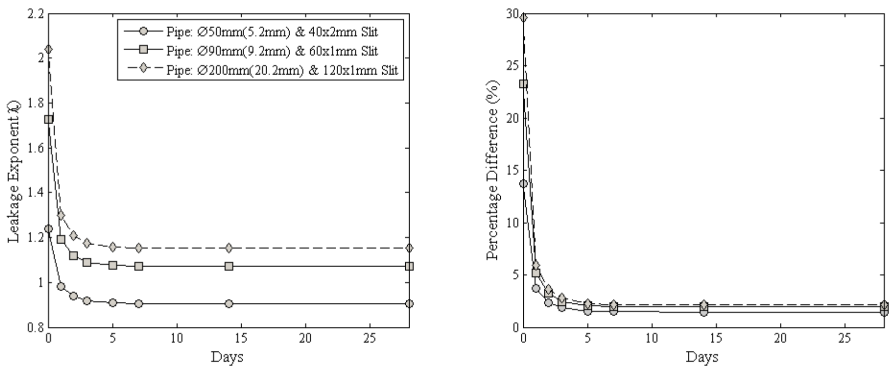

Fig. 3. (Left) Fitted leakage exponent dependence on simulated leak age (Right) Percentage difference between simulated leak flow data and fitted model predictions dependent on leak age

The magnitude of the leakage exponent and the range of theoretical values for each test case was shown to increase with size of the leak and tended to a discrete constant value after 7 days in all cases. It can also be seen that there is an exponential decrease in the percentage difference between the simulated and fitted models with increasing age, i.e. longer loading history. The percentage difference reaches a constant limit of approximately 3% for all test cases. The largest percentage difference is associated with the largest leak (120x1 mm crack).

The analysis presented in Figure 3 emphasised the significance of the short term (<5 days) leak response with regards to the applicability of the leakage exponent characterisation of viscoelastic leaks. The use of the Generalised Orifice Equation assumes a one-to-one pressure-leakage relationship. Figure 4 are plots of the daily pressure-leakage relationship for Test Case 1 subject to a repeated diurnal pressure trace; simulated pressurisation starts at Time Series Day 1.

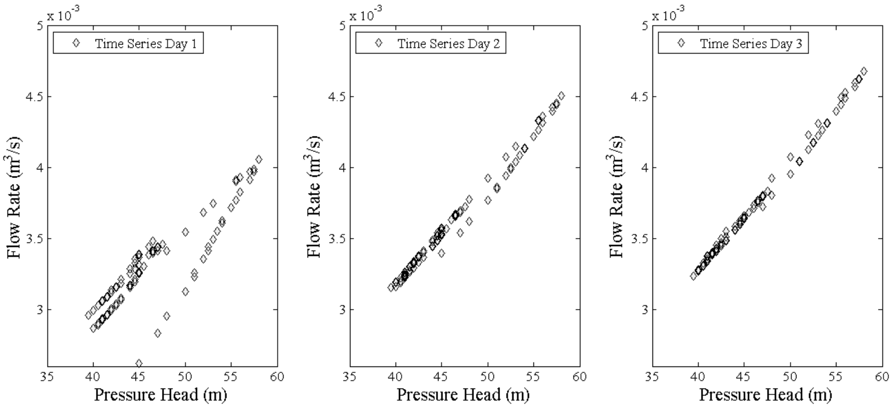

Fig. 4. Daily pressure (first three days after initial pressurisation) and leakage flow-rate relationship for longitudinal crack in viscoelastic pipe subject to typical DMA diurnal pressure cycle.

The results presented in Figure 4 highlight the hysterical behaviour of the leakage response confirming that the pressure-leakage response tends towards an approximate one-to-one correlation over time. This results in the observed reduction in fitted model percentage difference presented in Figure 3, as the data converges towards a constant error when reaching a pseudo-equilibrium state (constant hysteresis cycle).

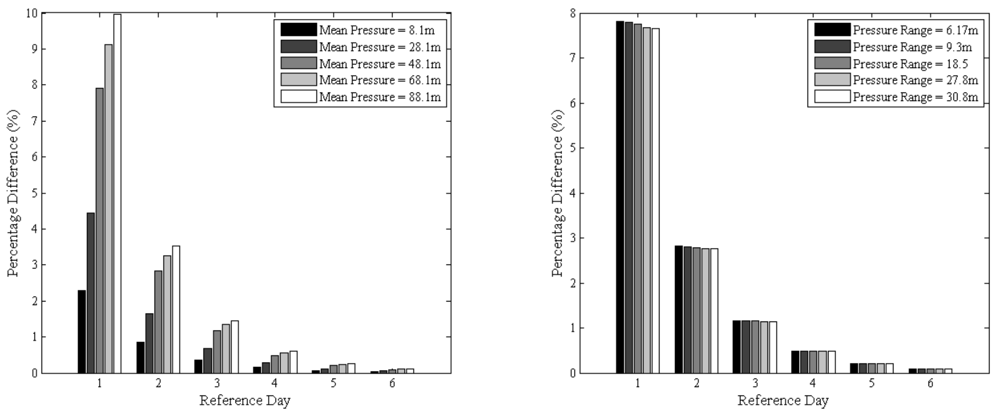

Fig. 5. Influence of pressure regimes on daily change in net leakage flow-rate for arbitrary longitudinal crack in viscoelastic pipe. Varied mean pressure (left) and varied pressure range with equal mean (right).

The time required to reach this state may be surmised to be a function of the material properties and the operating pressure regime, i.e. the maximum daily pressure and the daily pressure range. Figure 5 presents the percentage difference in daily net simulated leakage volume (e.g. percentage difference between Days 1 and 2) for Test Case 1 using scaled diurnal pressure data. The results confirm that the time taken to reach the pseudo-equilibrium state is a function of the pressure regime, most notably the magnitude of the mean pressure.

Finally a comparison of the leakage response of three different types of leak (fixed orifice, linear elastic crack and viscoelastic crack) subject to an identical extreme pressure transient was conducted. Figure 6 is the arbitrary pressure transient used for the analysis (sampling frequency = 1 Hz).

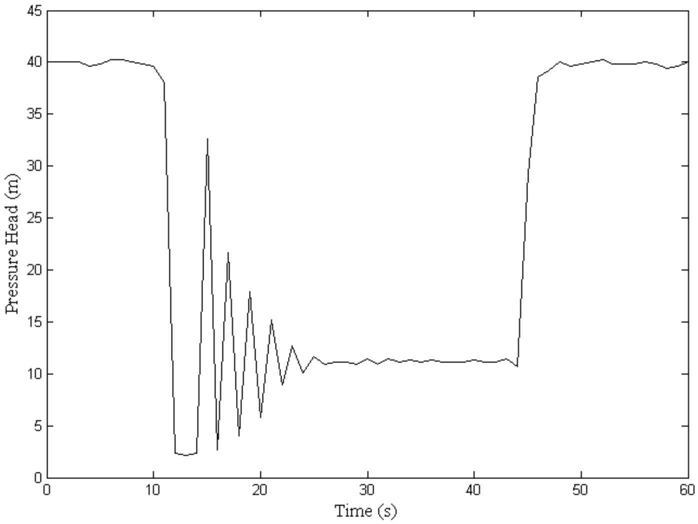

Fig. 6. Simulated pressure transient for fixed orifice, linear elastic leak and viscoelastic leak flow-rate comparison.

The results present an artificial scenario as each discrete leak type would result in a proportional damping effect on the pressure transient. However this would eliminate the comparability between results offered by modelling a repeatable pressure transient. Figure 7 are the leakage responses, calculated using Equation 2, for the three leak types described, with equal area prior to the pressure transient initialisation and a constant theoretical discharge coefficient.

It is clear that the short term leakage response is highly dependent on the material properties. Whilst the initial leak areas under pseudo-static pressure (t=0s) are equal, the pressure (and time, for the viscoelastic leak) dependence result in a severe disparity of time series leakage behaviour due to the individual structural dynamics of each test case.

5. Discussion

Leakage assessment is a crucial tool for quantifying and mitigating the effects of leakage within the overall sustainability of water distribution systems. Modelling using MNF analysis is a common methodology to assess the levels of leakage within a DMA assuming a one-to-one pressure-leakage relationship. The results presented herein show that this approach, whilst not theoretically applicable to time and pressure dependent leaks in viscoelastic pipes, provides a good numerical approximation of the leakage behaviour of such complex leaks, in particular the net leakage volume over a 24 hour time period. The accuracy of the leakage exponent as an estimator of the net leakage response is a function of the age of the leak, pressure regime and the material properties. In practice, most leaks that are captured by any MNF analyses will be older than 5 days and therefore the associated error due to the viscoelastic properties of the leakage response will be minimised. The associated error is not cumulative if the pressure-leakage relationship remains in a constant hysteresis cycle. This in itself is dependent on the pressure regime, and therefore any significant changes in the diurnal pattern (pressure steps) may result in diversion from this pseudo-equilibrium state, thus increasing the fitted model error. The leakage exponent methodology for characterising the leakage response of an individual

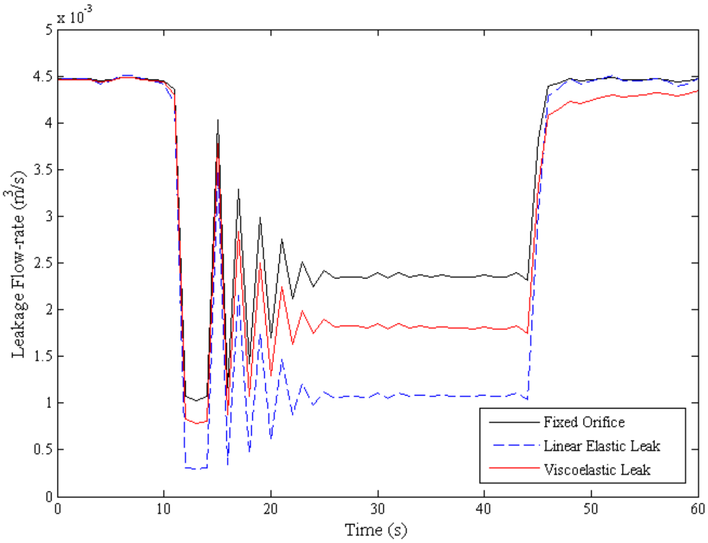

Fig. 7. Significance of viscoelastic behaviour of longitudinal crack in a plastic pipe subject to an extreme pressure transient.

leak or combination of leaks (e.g. both linear and viscoelastic leaks) may only be regarded as an estimator of the true response. This is reflected in the work conducted by [1] who showed that the fitting of the leakage exponent is a function of the pressure regime. Equation 3 is an example of an arbitrary system where the total losses are comprised of background leakage and leaks from fixed area orifices and linear and viscoelastic type leaks.

$$Q_{Leakage} = Q_{Background} + Q_{Orifice} + Q_{Linear} + Q_{Viscoelastic} = c_1 H^{0.5} + c_2 H^{0.5} + c_3 H^{1.0} + c_4 H^{1.1} \quad (3)$$

$$cH^{\lambda} \neq c_1 H^{0.5} + c_2 H^{0.5} + c_3 H^{1.0} + c_4 H^{1.1} \quad (4)$$

There is no equivalence between Equation 1 and 3 as shown in Equation 4, and therefore the Generalised Orifice Equation given in Equation 1 merely represents a numerical likeness (simplified fit) of the true coupled characteristic leakage behaviour. Nevertheless in practice this approach has been demonstrated, herein and in other published work, as a highly effective and efficient assessment tool for leakage management practitioners in the water industry.

In addition to the results presented, the influence of sampling-rate on the accuracy of the MNF analysis approach was also assessed but was shown to have negligible influence. Increased sampling rate is of particular significance for analyses such as leakage detection and leakage control. Leakage detection/localisation methodologies such as inverse transient analysis (ITA) depend on an understanding of the time-dependent leakage response. Figure 7 shows that the pressure and time dependence of the leak area is therefore of greater significance over short time periods (< 5 seconds) irrespective of the loading history. The importance of this is in the development of leak localisation methodologies which typically assume a fixed area orifice within the ITA methodology. Alongside this, the short term response is also important for assessing the risk of contaminant intrusion due to the existence of a external contaminant to a leak and a driving head. Equivalent linear-elastic leak area models may provide a conservative risk assessment as they assume the leak returns to small instantaneous size compared to the retarded leak area closure of cracks in viscoelastic pipe.

6. Conclusion

The investigation presented within this paper showed that the leakage exponent fitting methodology using MNF analyses, does provide a good estimate for the leakage response of cracks in viscoelastic pipes, dependent on the age of the failure and the explicit pressure regime (max pressure and pressure range). It may therefore be concluded that leakage assessment based on MNF analysis is an effective means of estimating the total real losses from a DMA based on a small amount of input data, irrespective of the specific pipe material. The significance of the material rheology is exaggerated when considering shorter analysis time periods, most notably for the response to pressure transients, fundamental to existing and developing leakage localisation and control strategies.

References

[1] J. E. van Zyl, A. M. Cassa, Modeling elastically deforming leaks in water distribution pipes, Journal of Hydraulic Engineering 140 (2014) 182–189.

[2] J. Thornton, A. Lambert, Progress in practical prediction of pressure : leakage , pressure : burst frequency and pressure : consumption relationships, in: IWA Special Conference - Leakage 2005, Halifax, Canada, 2005, pp. 1–10.

[3] S. Fox, R. Collins, J. Boxall, Dynamic Leakage: Physical Study of the Leak Behaviour of Longitudinal Slits in MDPE Pipe, Procedia Engineering 89 (2014) 286–289.

[4] M. Ferrante, C. Massari, B. Brunone, S. Meniconi, Experimental evidence of hysteresis in the head-discharge relationship for a leak in a polyethylene pipe, Journal of Hydraulic Engineering 137 (2011) 775–780.

[5] C. Massari, M. Ferrante, B. Brunone, S. Meniconi, Is the leak head-discharge relationship in polyethylene pipes a bijective function?, Journal of Hydraulic Research 50 (2012) 409–417.

[6] A. M. Cassa, J. E. van Zyl, R. F. Laubscher, A numerical investigation into the effect of pressure on holes and cracks in water supply pipes, Urban Water Journal 7 (2010) 109–120.

[7] R. Puust, Z. Kapelan, D. A. Savic, T. Koppel, A review of methods for leakage management in pipe networks, Urban Water Journal 7 (2010) 25–45.

[8] X. Wang, M. F. Lambert, A. R. Simpson, J. A. Liggett, J. P. Vtkovsky, Leak Detection in Pipelines using the Damping of Fluid Transients, Journal of Hydraulic Engineering 128 (2002) 697–711.

[9] J. May, Leakage, pressure and control, in: BICS International Conference on Leakage Control, London, UK, 1994.

[10] H. E. Mutikanga, S. K. Sharma, K. Vairavamoorthy, Methods and Tools for Managing Losses in Water Distribution Systems, Journal of Water Resources Planning and Management 139 (2013) 166–174.

[11] British Standards Institution, BS EN 12201-2:2011 : Plastic piping systems for water supply, and for drainage and sewerage under pressure Polyethylene (PE) drainage and Part 2 : Pipes, 2011.